



**QUEEN'S
UNIVERSITY
BELFAST**

Aerodynamic optimization using Adjoint methods and parametric CAD models

Hewitt, P., Marques, S., Robinson, T., & Agarwal, D. (2016). *Aerodynamic optimization using Adjoint methods and parametric CAD models*. Paper presented at European Congress on Computational Methods in Applied Sciences and Engineering, Athens, Greece.

Document Version:
Other version

Queen's University Belfast - Research Portal:

[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights
© 2016 The Authors

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Aerodynamic optimization using Adjoint methods and parametric CAD models

ECCOMAS Congress 2016

P. Hewitt S. Marques T. Robinson D. Agarwal
@qub.ac.uk

School of Mechanical and Aerospace Engineering
Queen's University Belfast



Contents

- Motivation
- CAD parameterisation
- Gradient Calculation
- Onera Wing
- NLR 7301
- Conclusions

Outline

- 1 Motivation
- 2 Gradient Calculation
- 3 Onera Wing Test Case
- 4 NLR 7301
- 5 Conclusions

Motivation

- Perform high-fidelity aerodynamic optimisation

Motivation

- Perform high-fidelity aerodynamic optimisation
- Increase flexibility of Adjoint Based Optimisation

Motivation

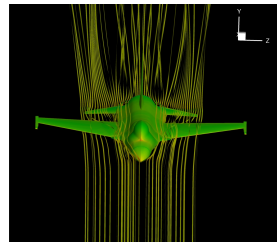
- Perform high-fidelity aerodynamic optimisation
- Increase flexibility of Adjoint Based Optimisation
- Enable use of parametric CAD model in optimisation

Motivation

- Perform high-fidelity aerodynamic optimisation
- Increase flexibility of Adjoint Based Optimisation
- Enable use of parametric CAD model in optimisation
- Efficient calculation of parametric sensitivities for CAD based design variables

Motivation

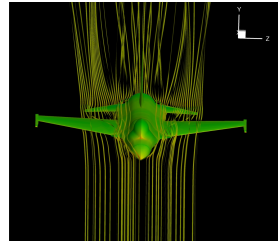
There are two main challenges to perform high-fidelity aerodynamic optimisation



Motivation

There are two main challenges to perform high-fidelity aerodynamic optimisation

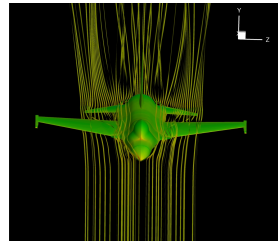
- Computational Cost
 - Gradient Based Optimisation



Motivation

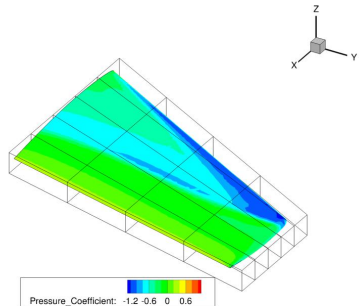
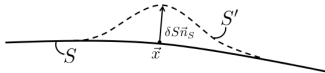
There are two main challenges to perform high-fidelity aerodynamic optimisation

- Computational Cost
 - Gradient Based Optimisation
- Large number of parameters
 - Adjoint Methods



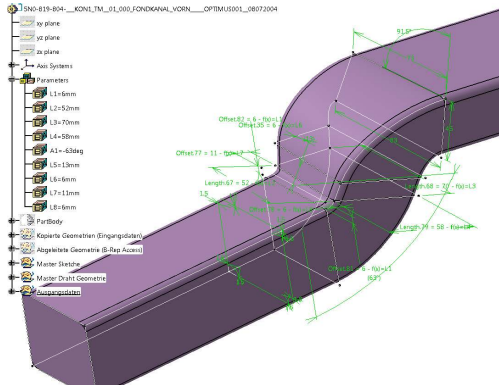
Motivation

In CFD based optimisation, parameterisations are usual built in the software



Motivation

The objective of this work is to integrate parameters used by CAD designers with high-fidelity analysis and optimisation.



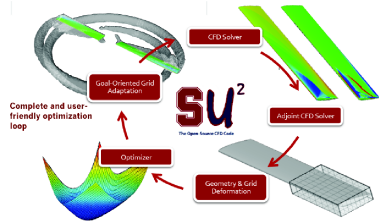
Outline

- 1 Motivation
- 2 Gradient Calculation**
- 3 Onera Wing Test Case
- 4 NLR 7301
- 5 Conclusions

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University



SU^2

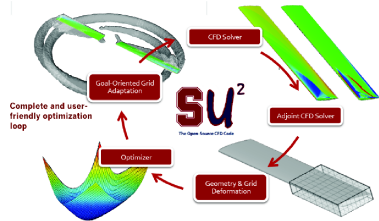
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University
- General purpose PDE solution methods



SU^2

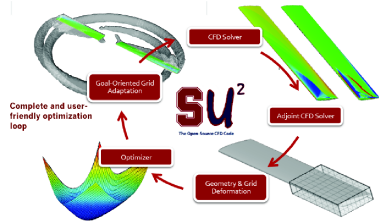
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University
- General purpose PDE solution methods
- Range of numerical schemes available (JST, ROE, MG, Euler-Implicit,...)



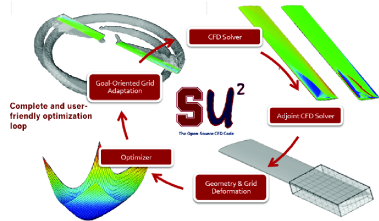
SU²
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University
- General purpose PDE solution methods
- Range of numerical schemes available (JST, ROE, MG, Euler-Implicit, ...)
- **Independent Mesh deformation/adaptation modules**



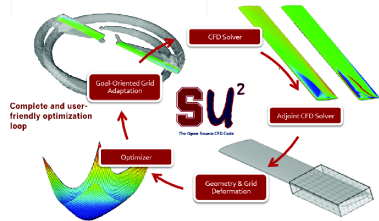
SU²
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University
- General purpose PDE solution methods
- Range of numerical schemes available (JST, ROE, MG, Euler-Implicit, ...)
- **Independent Mesh deformation/adaptation modules**
- **Continuous Adjoint Solver**



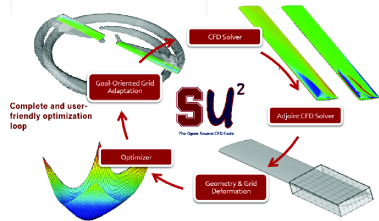
SU²
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

SU^2

SU^2 is an open-source CFD/Adjoint optimisation framework¹

- Developed at Stanford University
- General purpose PDE solution methods
- Range of numerical schemes available (JST, ROE, MG, Euler-Implicit, ...)
- Independent Mesh deformation/adaptation modules
- Continuous Adjoint Solver
- Independent Gradient Calculation module



SU²
The Open-Source CFD Code

¹images taken from <http://su2.stanford.edu/>

Gradient Based Optimisation

Gradient Calculation

$$\underbrace{\begin{bmatrix} \frac{\partial f}{\partial A_1} \\ \frac{\partial f}{\partial A_2} \\ \vdots \\ \frac{\partial f}{\partial A_n} \end{bmatrix}}_{\text{Gradients}} = \underbrace{\begin{bmatrix} \frac{\partial x_1}{\partial A_1} & \dots & \frac{\partial x_m}{\partial A_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_1}{\partial A_n} & \dots & \frac{\partial x_m}{\partial A_n} \end{bmatrix}}_{\text{Design Velocities}} \underbrace{\begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \frac{\partial f}{\partial x_2} \\ \vdots \\ \frac{\partial f}{\partial x_m} \end{bmatrix}}_{\text{Surface Sensitivities}}$$

- $\frac{\partial f}{\partial A_i}$ - Gradient
- $\frac{\partial x_j}{\partial A_i}$ - Design Velocities
- $\frac{\partial f}{\partial x_j}$ - Surface Sensitivities

Gradient Based Optimisation

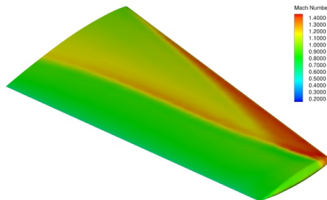
Gradient Calculation

$$\underbrace{\begin{bmatrix} \frac{\partial f}{\partial A_1} \\ \frac{\partial f}{\partial A_2} \\ \vdots \\ \frac{\partial f}{\partial A_n} \end{bmatrix}}_{\text{Gradients}} = \underbrace{\begin{bmatrix} \frac{\partial x_1}{\partial A_1} & \cdots & \frac{\partial x_m}{\partial A_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_1}{\partial A_n} & \cdots & \frac{\partial x_m}{\partial A_n} \end{bmatrix}}_{\text{Design Velocities}} \underbrace{\begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \frac{\partial f}{\partial x_2} \\ \vdots \\ \frac{\partial f}{\partial x_m} \end{bmatrix}}_{\text{Surface Sensitivities}}$$

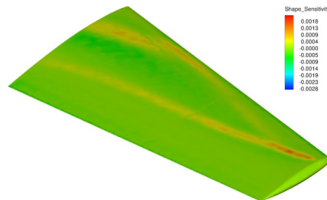
- $\frac{\partial f}{\partial A_i}$ - Gradient
- $\frac{\partial x_j}{\partial A_i}$ - Design Velocities
- $\frac{\partial f}{\partial x_j}$ - Surface Sensitivities

Surface Sensitivities

Flow sensitivity to surface obtained from adjoint solver (SU^2)



FLOW SOLUTION



ADJOINT SOLUTION

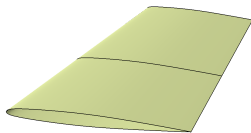
Design Velocities

Gradient Calculation

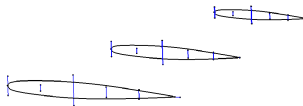
$$\underbrace{\begin{bmatrix} \frac{\partial f}{\partial A_1} \\ \frac{\partial f}{\partial A_2} \\ \vdots \\ \frac{\partial f}{\partial A_n} \end{bmatrix}}_{\text{Gradients}} = \underbrace{\begin{bmatrix} \frac{\partial x_1}{\partial A_1} & \cdots & \frac{\partial x_m}{\partial A_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial x_1}{\partial A_n} & \cdots & \frac{\partial x_m}{\partial A_n} \end{bmatrix}}_{\text{Design Velocities}} \underbrace{\begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \frac{\partial f}{\partial x_2} \\ \vdots \\ \frac{\partial f}{\partial x_m} \end{bmatrix}}_{\text{Surface Sensitivities}}$$

- $\frac{\partial f}{\partial A_i}$ - Gradient
- $\frac{\partial x_j}{\partial A_i}$ - Design Velocities
- $\frac{\partial f}{\partial x_j}$ - Surface Sensitivities

CAD parameterisation

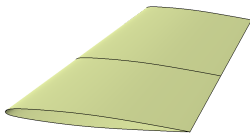


CATIA geometry

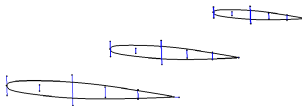


27 CATIA Parameters

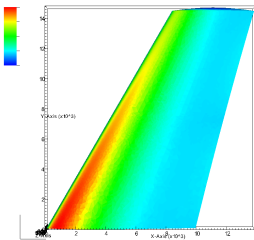
CAD parameterisation



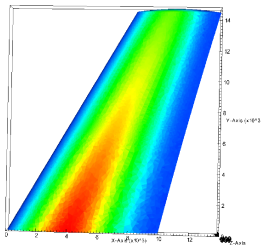
CATIA geometry



27 CATIA Parameters

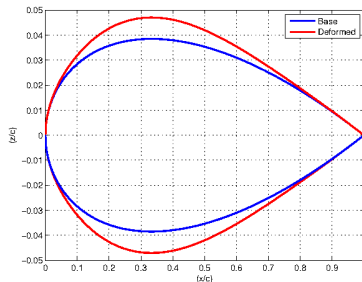


Design Velocities Param.1



Design Velocities to Param.3

Deform Surface



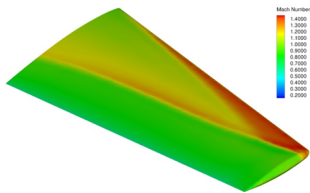
Use design velocities and mesh deformation module (linear elasticity) to deform surface CFD mesh.

Outline

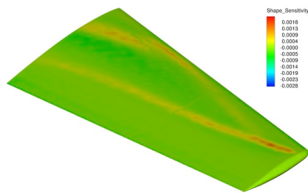
- 1 Motivation
- 2 Gradient Calculation
- 3 Onera Wing Test Case**
- 4 NLR 7301
- 5 Conclusions

Flow and Adjoint Solutions

Start the process by computing the flow and adjoint solution



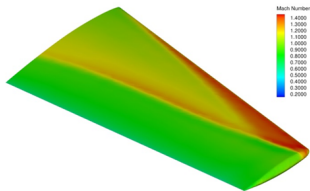
FLOW SOLUTION



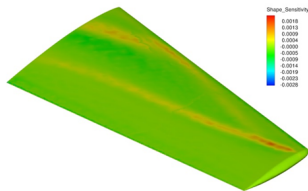
ADJOINT SOLUTION

Flow and Adjoint Solutions

Start the process by computing the flow and adjoint solution



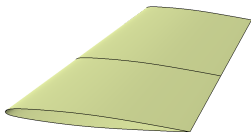
FLOW SOLUTION



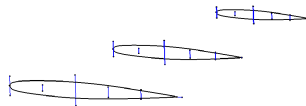
ADJOINT SOLUTION

and at the same time

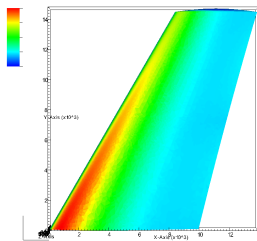
Geometric Sensitivities



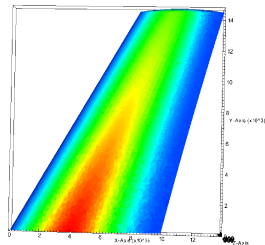
CATIA geometry



27 CATIA Parameters



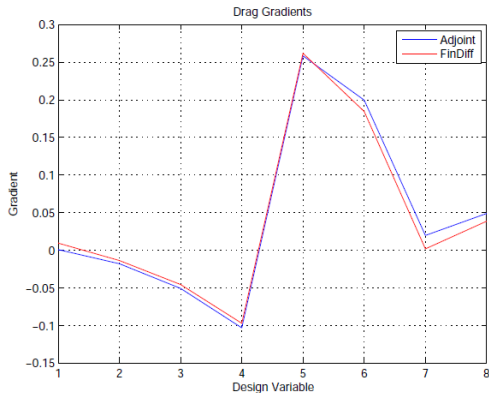
Geometry Sensitivity to Param.1



Geometry Sensitivity to Param.3

Gradient Validation

Compute gradient for optimiser:



Optimiser returns updated parameter values, which is used to create new CAD model and new design velocities calculated ...

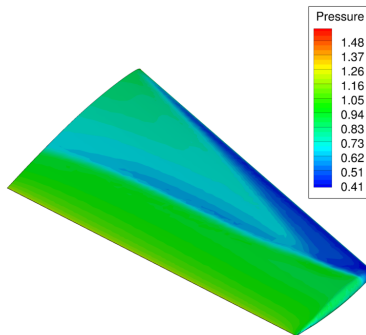
Onera Wing Drag Minimization

Transonic Test Case – Inviscid Calculation

$$M_{\infty} = 0.8395; \alpha = 3.06^{\circ}$$

$$\min C_D$$

$$\text{subject to: } C_L > 0.283$$

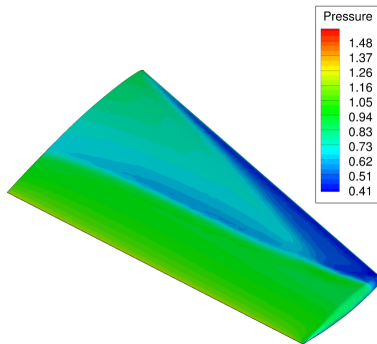


BASELINE

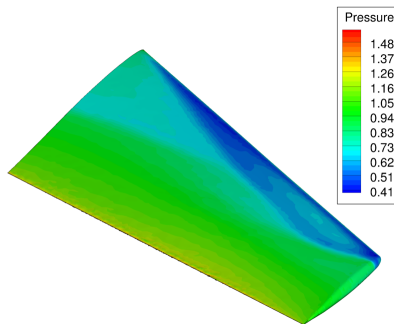
Onera Wing Drag Minimization

Transonic Test Case – Inviscid Calculation

$$M_{\infty} = 0.8395; \alpha = 3.06^{\circ}$$

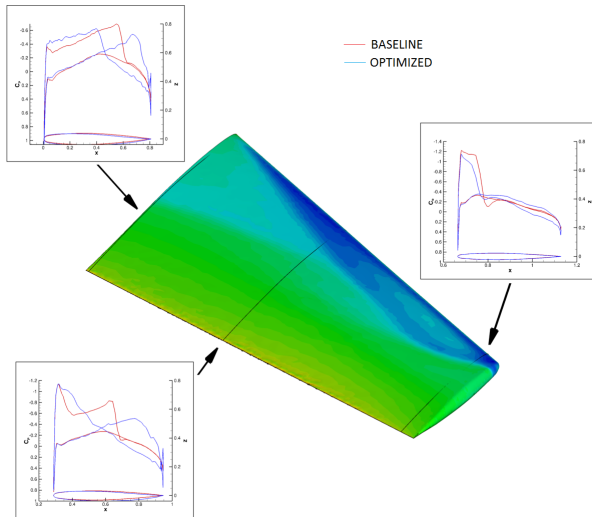


BASELINE

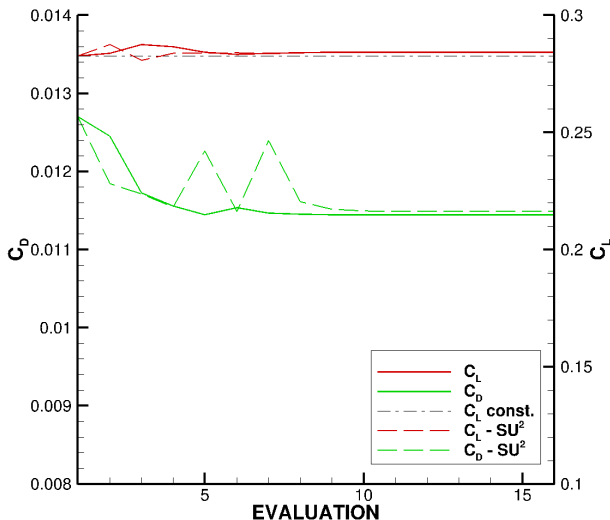


OPTIMIZED

Onera Wing Drag Minimization



Onera Wing Drag Minimization



Outline

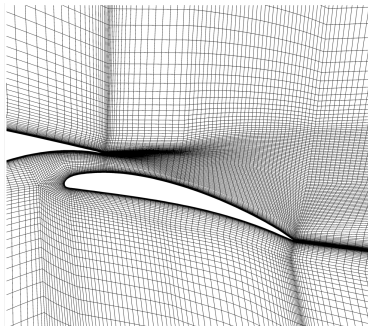
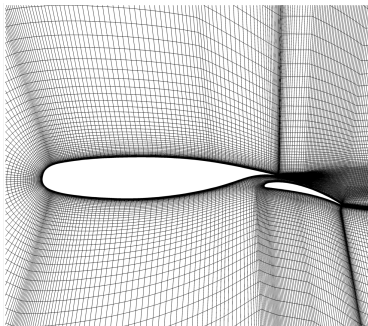
- 1 Motivation
- 2 Gradient Calculation
- 3 Onera Wing Test Case
- 4 NLR 7301**
- 5 Conclusions

NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D

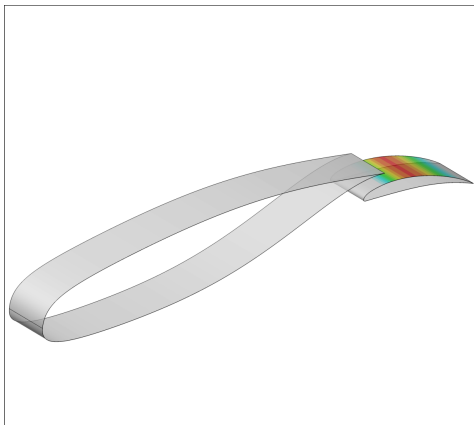


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

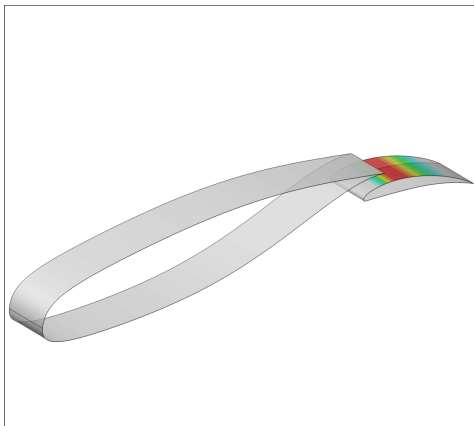


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

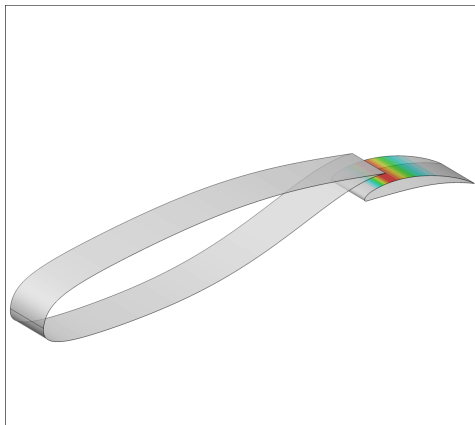


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

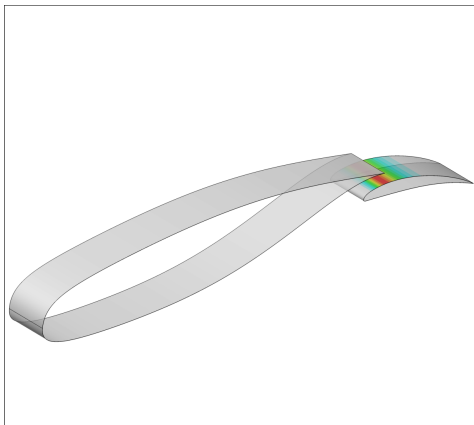


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

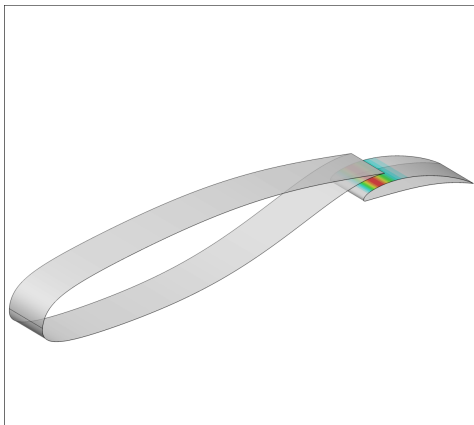


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

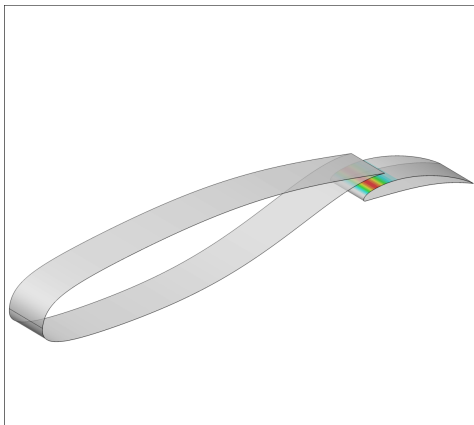


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters



NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

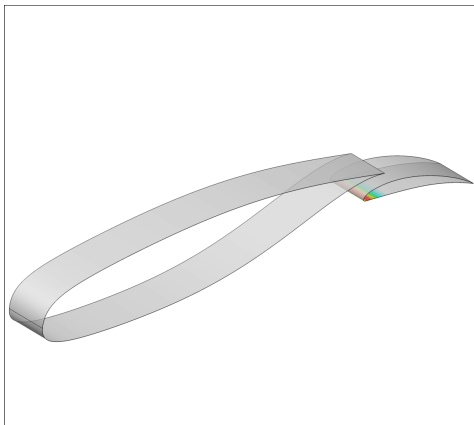


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

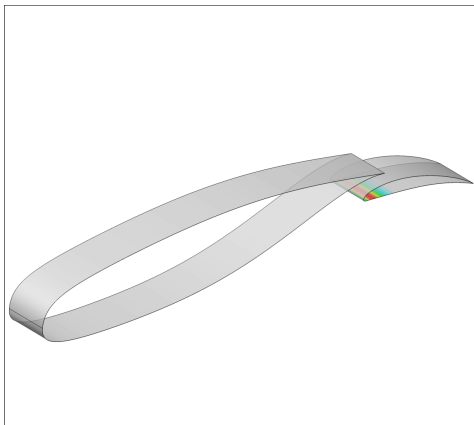


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

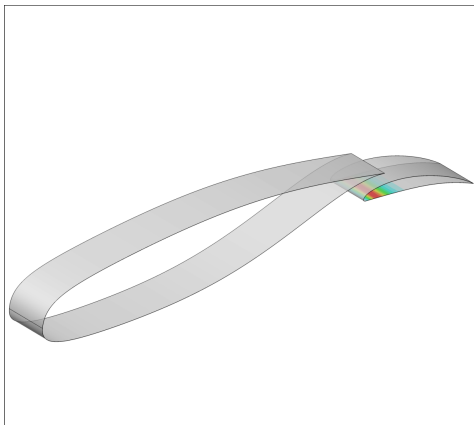


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

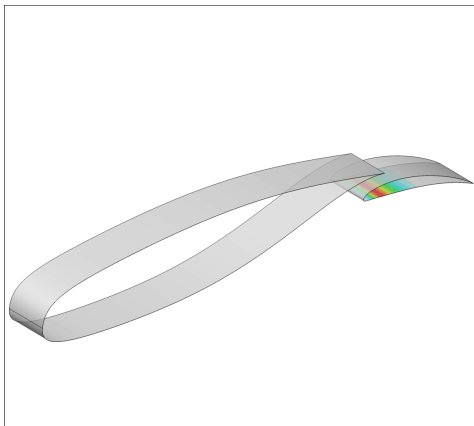


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

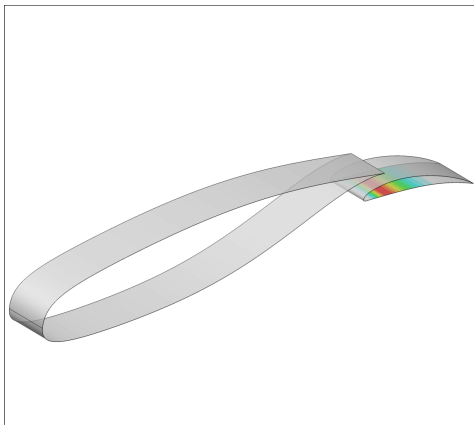


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

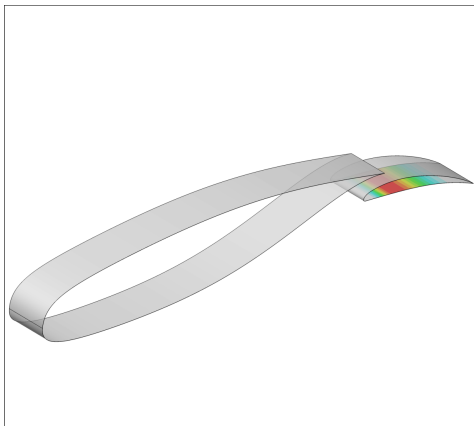


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

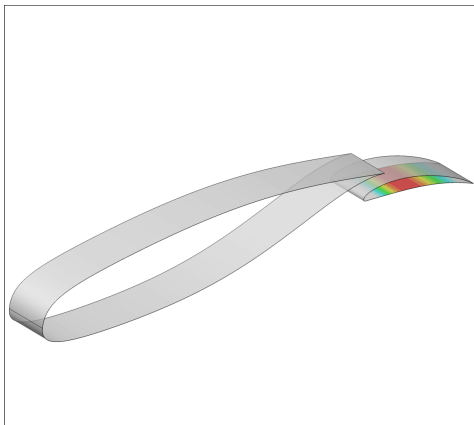


NLR 7301 High-Lift Case

High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

Maximise L/D ; 14 CATIA Parameters

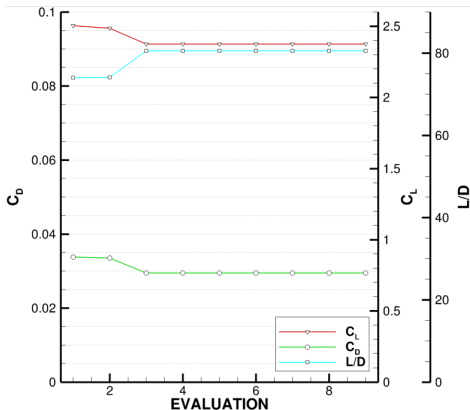


NLR 7301 High-Lift Case

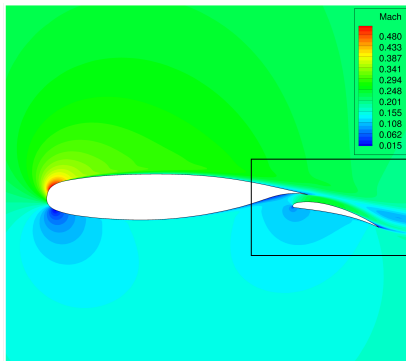
High-Lift Test Case – RANS Calculation (using SA)

$M_\infty = 0.185$; $\alpha = 6^\circ$; $Re = 2.51 \times 10^6$;

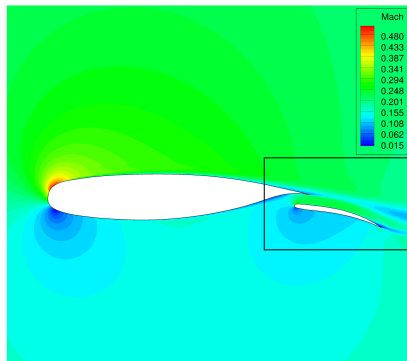
Maximise L/D ; 14 CATIA Parameters



NLR 7301 High-Lift Case

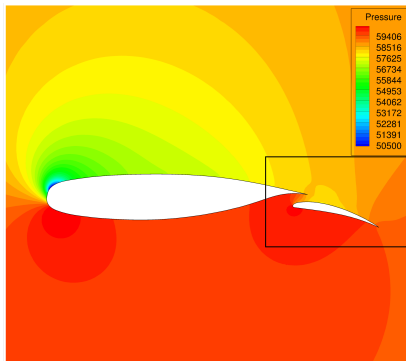


Original

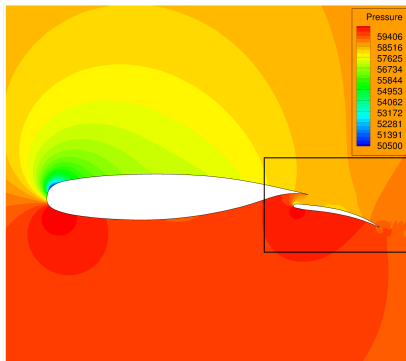


Optimised

NLR 7301 High-Lift Case



Original



Optimised

Outline

- 1 Motivation
- 2 Gradient Calculation
- 3 Onera Wing Test Case
- 4 NLR 7301
- 5 Conclusions**

Conclusions

Conclusions:

Conclusions

Conclusions:

- CAD parameterisations were coupled with a CFD/Adjoint optimisation framework, SU^2

Conclusions

Conclusions:

- CAD parameterisations were coupled with a CFD/Adjoint optimisation framework, SU^2
- Model deformation and geometric sensitivities are calculated outside CFD solver

Conclusions

Conclusions:

- CAD parameterisations were coupled with a CFD/Adjoint optimisation framework, SU^2
- Model deformation and geometric sensitivities are calculated outside CFD solver
- Alternative approach does not compromise optimisation efficiency with respect to native parameterisations

Q & A

Thank you for your attention

Questions Welcome